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Urban arterial travel time evaluation using Bluetooth data

Bluetooth verisi kullanarak kentsel arterlerde seyahat süresinin değerlendirilmesi

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Urban Arterial Travel Time Evaluation using Bluetooth Data

Highlights

- *Bluetooth based traffic data for travel time estimation*
- *Level of Service based urban traffic monitoring with Bluetooth technology*
- *Travel time variations during peak hours*
- *Outlier detection*

Graphical Abstract

The variations in travel times for each corridor were examined statistically, which were later used to evaluate corridors level of service (LOS) for urban traffic monitoring.

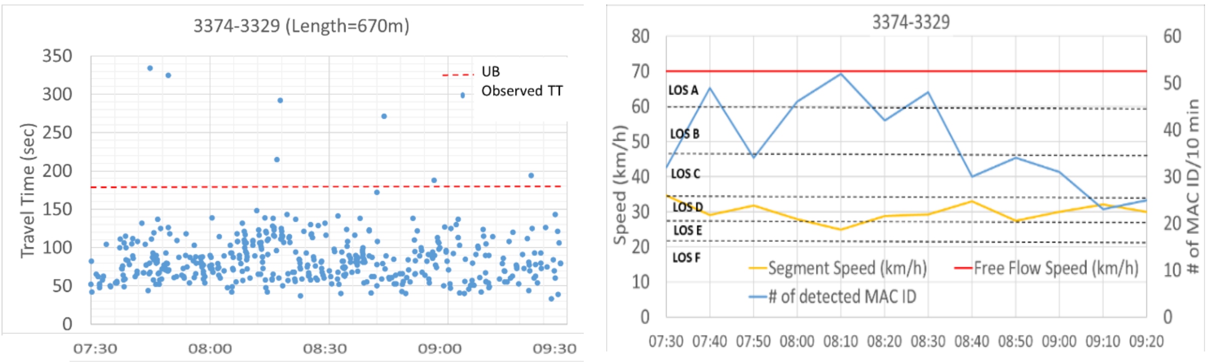

Figure. Distribution of travel times, corridor-based estimated average speeds, LOS values, and # of detected Bluetooth MAC IDs for the morning peak.

Aim

This study aims to i.) investigate the variability and reliability of the travel times during congested peak hours for urban arterials with traffic signals, and ii.) examine its potential for urban traffic monitoring by employing Level of Service concept to Bluetooth (BT)-based traffic data.

Design & Methodology

The evaluation methodology for urban travel time evaluation started with the preliminary statistical evaluation to identify the mean, standard deviation, minimum and maximum values of the travel times and interquartile range values in which the latter was used to determine the outliers in Bluetooth data. Eliminating the outliers from BT data enabled to investigate the variability and distribution of travel times of the motorized vehicles. Secondly, Highway Capacity Manuel (2010) guideline was utilized (based on the reductions in travel speed as a percentage of the free-flow speed) to define the Level of Service (LOS) for monitoring urban traffic for each study corridors.

Originality

Due to the lack of the ground truth data to compare the travel time reliability of the BT-based travel times, this study proposed a methodology to i.) statistically investigate travel time distributions, ii.) define an upper bound travel time value for the study corridors. Furthermore, as a regular measure for urban arterial management, Highway Capacity Manuel (2010) procedure was employed to estimate level of service. Thus, it could be possible to observe the variations in traffic conditions over time which makes our study novel.

Findings

The Bluetooth data had considerable success for estimating travel times in case of eliminating the outliers from BT-based traffic data. Directional traffic conditions could be observable by employing the LOS concept concluding that BT-based traffic data can be used a traffic data source for urban traffic monitoring purposes.

Conclusion

In overall, the BT-based traffic data had a considerable penetration rate for the study corridor ranging from 10.9% to 11.2% which enabled to estimate the travel times as well as the traffic condition over time. Also, filtering process must be carefully handled to eliminate the outliers from travel time data.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Bluetooth Verisi Kullanarak Kentsel Arterlerde Seyahat Süresinin Değerlendirilmesi

Araştırma Makalesi/Research Article

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ÖZ

Bir kentsel arterde hızın veya seyahat süresinin güvenilir bir şekilde tahmin edilmesi, trafiğin daha iyi yönetilmesi için gereklidir. Geleneksel olarak, bu tür veriler döngü detektörleri, endüktif döngüler, video kameralar aracılığıyla toplanır. Fakat kurulum maliyetlerinin yüksek olması nedeniyle bu cihazları trafikteki her bir noktaya yerleştirmek mümkün değildir. Son zamanlarda, Bluetooth (BT) teknolojisi, i) düşük kurulum maliyeti ve ii) 24 saatlik periyotta bile sürekli veri sağlama avantajı nedeniyle bir trafik veri kaynağı olarak yaygın bir şekilde kullanılmaktadır. BT tabanlı trafik verileri, Bluetooth cihazlarının tekil Ortam Erişim Kontrollerinin (MAC) zaman bazlı olarak kaydedilmesi prensibine dayanır. Birden fazla farklı konumda aynı MAC adreslerinin algılanması, yolculukların Başlangıç ve Varış noktalarının yanı sıra seyahat süresi bilgilerinin de tahmin edilmesini sağlar. Bu çalışmada, Mersin ilinde bulunan ana sinyalize kentsel arterlerden elde edilen BT verileri kullanarak hesaplanan seyahat sürelerinin dağılımı incelenmiştir. Veriler, hafta içi iki gün 07:30-09:30 (sabah zirve saatleri) arasındaki ana arterler üzerindeki 5 ardışık sinyalize kavşaktan toplanmıştır. Sonuç olarak, yeterli örneklem düzeyi sağlandığı için, veriler seyahat sürelerini tahmininde ve kentsel trafiğin izlenmesinde başarılı olmuştur. Bununla birlikte, motorlu hareketleri motorsuz olanlardan ayırmak için filtreleme işlemi dikkatlice yapılması gerektiği sonucuna varılmıştır.

Anahtar Kelimeler: Bluetooth teknolojisi, seyahat süresi tahmini, seyahat süresi dağılımı, trafik verisi.

Urban Arterial Travel Time Evaluation using Bluetooth Data

ABSTRACT

Reliable estimation of speed or travel time (TT) of an urban arterial is the fundamental task for better management of the traffic. Traditionally, such data are collected via loop detectors, inductive loops, video cameras, but their installation cost were not always allowed to locate every specific point. Recently, Bluetooth (BT) technology has been widely used as a traffic data source due to the i) low installation cost, and ii) providing continuous data even 24-h period. The principle of BT-based traffic data is simply capturing the timestamped of the unique Media Access Control (MAC) of Bluetooth devices. Detecting the same MAC addresses from multiple different locations enabled to estimate the Origin and Destination (O-D) of the trips and travel time information. This study evaluates the distribution of TT information from different perspectives in which BT-based traffic data were obtained from five consecutive signalized intersections located in Mersin, Turkey during morning peak hours of 07:30-09:30 for the two weekdays. The results indicated that the data had considerable success in estimating travel times and urban traffic monitoring with adequate sampling rates. However, the filtering process must be carefully handled to distinguish the motorized movements from non-motorized ones.

Keywords: Bluetooth technology, travel time estimation, travel time distribution, traffic data.

1. INTRODUCTION

Accurate and reliable estimation of travel time (TT) or traffic state in an urban arterial is essential for better traffic management and control. Traditionally, TT data can be collected from various traffic data sources such as magnetic loops, sensors and video cameras. However, their installment and maintenance costs make them more difficult to install at many locations due to the complexity of the urban roads (existence of entry and exit points), and it is also more difficult for local authorities due to the budget limitations [1]. Additionally, these devices only provide the traffic information of the located sections [1]. On the other hand, the more recent methods, floating cars, probe vehicles and Bluetooth, provide TT value of a broad coverage area along the urban road networks. Bluetooth (BT) technology has been widely used as a traffic data source due to the i) low installation cost, and ii) providing continuous data even 24-h period. The principle of BT-based traffic data is simply capturing the timestamp of the unique media access control (MAC) of Bluetooth devices. BT readers send signals for every time interval (varying from 10 sec to 40 sec) to a particular circular area, namely the detection zone. This detection zones range is generally within 1 m to 100 m based on the BT reader class [2].

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As for literature on the Bluetooth-based studies, the accuracy or variability of the travel times has been investigated particularly for freeways or multilane highways [3-7], whereas there were limited studies regarding the travel time reliability for urban arterials controlled with traffic signals [8-10] which is the main focus of this study. For this purpose, BT-based travel time data was collected for two days (October 8-9, 2019) during morning peak hours (07:30-09:30) from five consecutive intersections located on major urban arterials in Mersin, Turkey. The variations in travel times for each consecutive BT reader location (named a corridor throughout the manuscript) were examined statistically. Secondly, individual TTs were converted to speed to investigate its potential for urban traffic monitoring. As a regular measure for urban arterial management, HCM [11] procedure was employed to estimate level of service (LOS) of the urban corridors. The results concluded its success for urban traffic monitoring with an adequate sampling rate.

2. LITERATURE REVIEW

BT-based traffic data has been frequently used in traffic analysis due to the higher sampling rate and low cost [12]. While some studies focused on the reliability of travel times for freeways or urban arterials [3-10], some other studies focused on the estimation of origin-destination matrix [2, 13-15], freeway performance evaluation [10, 16-17], traffic safety analysis [18], delay estimation for signalized intersections [19-21]. Since the focus of this study is to examine the reliability of TT data, it is useful to present the TT related studies in this section.

Diaz et al. [3] developed a Bluetooth-based traffic monitoring system to estimate vehicle travel times in real time. The success of the proposed model was evaluated under simulation environment considering both uninterrupted and interrupted flow conditions, in which more reliable TTs were obtained for the former one. The results indicated that 5-min aggregation in BT data generated reliable estimation values for the interrupted case. Additionally, the significance of detecting the outliers from BT were discussed. Araghi et al. [4] evaluated the TT reliability by comparing the TT values of BT and GPS suggesting a correlation of 80%. TT reliability of BT data was also investigated in different traffic flow and weather conditions for two segments along the freeway section in Indianapolis, USA [6]. TT reliability was significantly decreased from adverse weather conditions. The authors also proposed a regression model to quantify the effect of the traffic condition on TT reliability, but the model parameters were not found significant. Haghani [5] utilized Floating Car Data (FCD) as ground truth to evaluate the reliability of the BT data. TTs were converted to speed values, and statistical evaluation has done under for 4 speed categories as; i) speed below 30mph, ii) 30-45 mph, iii) 45 and 60 mph, and iv) speed above 60 mph. The results showed that BT speeds were not significantly different from the FCD for each category. Tufuor and Laurence [8] examined the TT reliability of BT-based traffic data for 0.5-mi urban arterial in Lincoln, Nebraska. TT distribution obtained from BT was found significantly different from the 6th edition of the Highway Capacity Manual (HCM-6). Liu et al. [7], focused on the accuracy of TTs for an urban arterial located in Perth, Wesern Australia. The results showed promising estimations if the filtering process can be implemented to BT data to eliminate the outliers. Similar conclusions were also reported in other studies [22-27].

In light of the existing literature, TTs can show different reliability for urban arterial because of a more challenging environment (existence of traffic signals and merging/diverging movements); however, TTs can be measured more accurately for uninterrupted flow conditions [5].

3. STUDY AREA

Bluetooth data used in this study were obtained from five different BT readers located on five signalized intersections along a major urban arterial in Mersin, Turkey (see Figure 1). The speed limit of the arterials in the east-west direction is 70 km/h (BT 3309 to BT 3311, BT 3374 to BT 3329), and it is 50 km/h for the south-north one (BT 3374 to BT 3310). The range of the BT readers used in this study is 100 m., which means that MAC IDs of the BT-based devices can be captured within the 100 m radius only. MAC ID is a 12-digit unique electronic identifier that serves as an electronic nickname. An example BT data set collected from different locations is presented in Table 1. *BT-ID* represents the location of the BT reader, *MAC ID* represents the detected unique nickname of the captured BT-based device, and *Time* column represents the detection time. If the same MAC ID is detected multiple times consecutively by the same BT sensor, it enables to evaluate intersection delays and level of service. Additionally, detection of the same MAC ID at different BT locations provides the derivation of the Origin-Destination (O-D) matrix and the real-time TTs of the urban corridors, which are the inevitable tasks for urban traffic management.

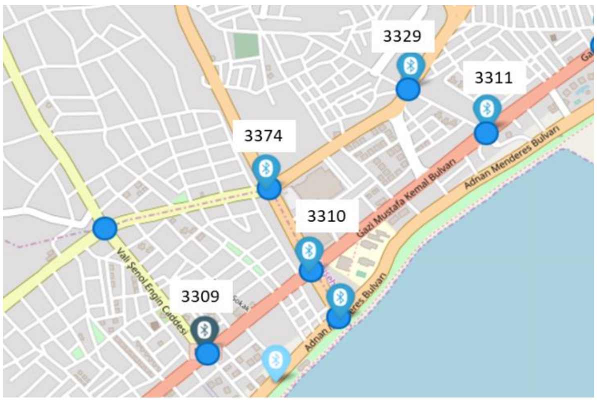

Figure 1. Location of the BT readers

Table 1. An example format of the BT data for the study corridor

BT-ID	MAC ID	Time
3374	9C:8D:7C:C1:20:8C	07:30:15
3348	FC:58:FA:CC:C1:A2	07:35:46
…	…	…
3309	2A:2C:22:D2:91:E3	08:15:07
3309	2A:2C:22:D2:91:E3	08:15:20
3329	2A:2C:22:D2:91:E3	08:17:52

4. EVALUATION METHODOLOGY

The methodology of the proposed study is composed of three main parts, as explained in detail below.

Analysis 1 - Descriptive Evaluation: This part covers the preliminary descriptive analysis of the detected MAC IDs for each BT reader separately. It will provide the number of detected BT-based devices by each BT reader. Thus, it can be possible to interpret whether the intersection performance, such as delay, could be evaluated or not.

Analysis 2 - O-D Matrix Determination: This process starts with the MAC ID matching of two consecutive BT readers to produce trip information. The algorithm simply captures the timestamps and location of the detected MAC IDs. Later the same MAC IDs are searched for whether are detected by other BT readers. If the same MAC ID is detected by more than two BT readers, the first and last BT readers location is considered origin and destination points, respectively. Therefore, it is possible to identify the origin and destination points of the trips in the studied area. At the end of this step, all trips between the same origin and destination locations are summed to obtain the O-D matrix.

Analysis 3 - Urban Travel Time Evaluation: Based on the findings from O-D matrix estimation, the traffic flows on the major corridors (BT 3309 – BT 3310; BT 3310 – BT 3311; BT 3374 – BT 3329) are used to evaluate directional TTs during the morning peak hours. The following analysis are used to evaluate the TTs:

- First preliminary statistical evaluation was performed to calculate the mean and quartile values (Q_1 to Q_3) of the TTs, which were later used to eliminate outliers (noisy values). As discussed earlier, it is necessary to distinguish motorized movements from nonmotorized ones in urban areas. The upper bound (UB) and lower bound (LB) of the TT values for each corridor is determined as:

$$TT_{UB,LB} = Q_3 \pm 1.5 * (Q_3 - Q_1) \qquad (1)$$

Therefore, TT values lower than the lower bound and greater than the upper bound are filtered out.

- After elimination of the outliers, distribution of the filtered TTs during the morning peak period is examined. TTs are converted to speed values to evaluate the Level of Service (LOS) of the study corridors. As discussed in Highway Capacity Manual [11], LOS for urban arterials is determined based on the reduction in speed as a percentage of the free-flow speed. The corresponding threshold values for each LOS condition is given in Table 2. Therefore, travel speed as a percentage of free flow speeds were calculated the LOS values.

Table 2. Average speed intervals and corresponding LOS values for urban roads [11]

LOS	Flow Condition	Travel speed as a percentage of free flow speed
A	Free flow conditions	>85%
B	Unimpeded flow condition	67%-85%
C	Stable flow	50%-67%
D	Approaching to unstable flow	40%-50%
E	Unstable flow	30%-40%
F	Congested flow	<30%

5. RESULTS

5.1 Descriptive evaluation results

The frequency of detected Bluetooth devices for each BT reader was examined under eight classes, as shown in Figure 2. The results showed that among 3990 unique MAC IDs from all BT readers for October 8, 2019, the majority of them were detected once for each BT reader, which constituted 58% at BT reader “3309” and 69% at BT reader “3374”. The MAC IDs, which were detected two times at a specific BT reader, accounted for 15%-20% and followed by the three-times and four-times with a percentage of almost 9% and 5%, respectively. This suggested that it is impossible to evaluate the intersection performance or delay since the majority of the BT devices were captured once at an intersection.

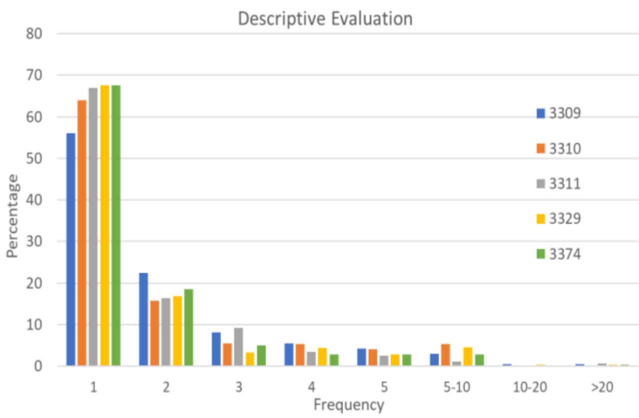

Figure 2. Descriptive evaluation results of detected MAC IDs for different BT readers on October 8, 2019

Despite the low percentage, some MAC IDs were also captured more than 20-times (see Figure 3) that can be considered as MAC IDs of nonmotorized vehicles such as pedestrians, bicycles, etc. Very similar results were observed for the second study day as well. Additionally, existing penetration rate of BT devices on the study corridor were determined. Video records have been taken from all approaches of two intersections where 3310 and 3374 BT-IDs were located. 11.2% and 10.9% penetration rates were calculated for these two BT-IDs, respectively.

5.2. O-D matrix estimation results

Among captured 3990 unique MAC IDs in October 8, 1253 of them produced trips which constituted the 31.4% (see Table 3). As for the October 9, 1248 trips were generated, which were slightly less than the first study day (see Table 4). The distribution of these trips among BT locations showed very similar results in which higher flow was observed from “3374” to “3329” with 241 and 254 trips for the study days, respectively. The results showed that the majority of the matched MAC IDs were observed in 7 O-D pairs (total detected trips >90 for each day) as shown in Tables 3 and 4; thus, among 20 O-D pairs, these 7 corridors were selected and used for TT analysis.

Table 3. O-D matrix of the study corridor during 07:30-09:30 on October 8, 2019

OD	3309	3310	3311	3329	3374	Total
3309		126	23	4	24	177
3310	95		159	15	48	317
3311	14	95		31	12	152
3329	4	7	79		97	187
3374	14	159	6	241		420
Total	127	387	267	291	181	**1253**

Table 4. O-D matrix of the study corridor during 07:30-09:30 on October 9, 2019

OD	3309	3310	3311	3329	3374	Total
3309		126	31	4	20	181
3310	110		135	13	49	307
3311	8	90		30	6	134
3329	5	7	64		127	203
3374	18	143	8	254		423
Total	141	366	238	301	202	**1248**

5.3. Urban Travel Time Analysis

Travel time statistics of the 7 selected corridors were evaluated by combining the study days travel data (see Table 5). Examining of the Raw TT statistics showed that there were much more variations in TTs for all corridors. For example, for the corridor 3374-3329 with a length of 670 m, average TT was calculated as 222.1 sec with a standard deviation of the 569.6 sec which was almost twice of the average value. These variations were also observable by comparing the minimum and the maximum TT values which were 33 sec to 4803 sec, respectively for the same corridor. Based on the IQR calculations discussed in Section 3, UB travel time values for each corridor were calculated. TT values greater than the determined upper bound value were assumed as outliers and were eliminated (see Table 5). The filtering process effect is clearly observable when the statistics of raw TT data was compared with the filtered ones. For example, for the same corridor, the average TT value was dropped to 82.6 sec with a standard deviation of 24.7 sec. The maximum travel time value was dropped from 4803 sec to 172 sec, which was an acceptable value. The UB travel time was calculated for this corridor as 179 sec.

It should be noted that the calculation of the lower bound of the TT values using the same formula produced negative TT values; thus, the filtering process was only applied to identify the UB values. Finally, travel time distributions were investigated for the 6 corridors where the corridor length is greater than 500 m visualized in Figure 3. The corridor where the highest MAC IDs were captured with *N*=495 (see Table 5), the distribution of the TTs showed that the majority was within the range of the 50-150 sec (see Figure 3) with the UB value of 179 sec. A similar trend was also observable for the remaining corridors; most of the TTs were fall into the range of 50-150 sec, but the UB value showed differences based on the different segment lengths, as expected.

To get an idea about the corridors traffic state, individual travel times were converted to individual speeds since the distance between two consecutive BT locations is known. Due to the low sampling rate of the BT data, at some minutes, no TT data were obtained for the corridor; thus, TTs were aggregated for 10-min intervals and the average speeds and # of detected MAC IDs were determined. Figure 4 illustrates the variations of the detected MAC IDs over time as well as the average speed of the road segment compared to the free flow speed value. The results revealed that:

- The highest detection was observed in corridor 3374-3329 with a range of 25-50 MAC ID/10-min. The average speed during the 07:30-09:30 were 30- 40 km/h in general (corresponds to LOS D) except at times 08:00-08:10 falling to 25 km/h, which was in LOS E condition.
- 3310-3311 and 3311-3310 corridors were in the free-flowing condition and no traffic congestion was detected.
- The severe traffic congestion was detected in corridors 3309-3310 and 3310-3309; average speeds were below the 20 km/h, which was LOS F condition.
- Except for the 3374-3329, detected BT MAC IDs were within a range of 10-30 MAC ID/10 min, which is adequate for urban traffic monitoring.

Table 5. Descriptive statistics results of raw and filtered TT for the selected corridors

	3374-3329	**3374-3310**	**3310-3311**	**3309-3310**	**3329-3374**	**3310-3309**	**3311-3310**
Raw TT Data Statistics							
# of Sample	495	302	294	252	224	205	185
Length (m)	670	391	875	521	670	521	875
Mean (sec)	222.1	141.3	234.9	413.7	397.9	325.7	459.2
Std. (sec)	569.6	372.5	601.5	1045.2	850.7	727.0	1077.4
Min. (sec)	33	15	47	36	37	33	40
Max.(sec)	4803	3573	3501	6533	5505	4274	5855
UB	179.0	151.0	171.6	216.5	233.4	237.0	205.5
Filtered TT Data Statistics							
# of Sample	446	273	265	216	184	178	159
Mean (sec)	82.6	50.1	83.4	89.1	84.8	95.6	85.1
Std. (sec)	24.7	24.9	26.6	33.6	32.6	41.0	31.7
Min. (sec)	33	21	47	36	37	33	40
Max. (Sec)	172	148	169	199	220	237	194

Figure 3. Corridor-based travel time distributions and corresponding UB values for the morning peak

Figure 4. Corridor based estimated average speeds, LOS values and # of detected Bluetooth MAC IDs for the morning peak

6. CONCLUSIONS

Due to the lack of the ground truth data to compare the travel time reliability of the BT-based travel times, this study provides a methodology to i.) statistically investigate travel time distributions, ii.) define an upper bound travel time value for the study corridors. Furthermore, Highway Capacity Manuel (2010) procedure was employed to estimate level of service. The results draw conclusions about the possible implementation of BT data such as urban corridor travel time variations and evaluation, O-D matrix estimation and LOS calculation for urban traffic monitoring. The main finding of this study revealed that it is very crucial to distinguish the vehicular movements from nonvehicular ones. So, filtering the data must be carefully handled.

As a conclusion, Bluetooth data had considerable success for estimating travel times in case of eliminating the outliers. Directional traffic conditions could be also observable by employing the LOS concept. As for the signalized intersection performance, it could not be possible since the majority of the MAC IDs were captured once at an intersection. In conclusion, BT-based traffic data can be used a traffic data source for travel time analysis and urban traffic monitoring with an adequate sampling rate ranging from 10.9% to 11.2%.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Oruc ALTINTASI: Performed analysis, interpreted the analysis results, wrote and organized the structure of the manuscript.

Mehmet Eray BALCI: Performed the analysis.

Murat OZEN: Interpreted the analysis results, wrote and organized the structure of the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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